

OBSERVATION OF NUCLEAR FUSION IN SONOLUMINESCENCE

- Progress, Future Challenges/Opportunities

by

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Prepared for Presentation
At Fermi National Accelerator Laboratory
July 14, 2004

THE ALLURE & CHALLENGES OF NUCLEAR FUSION

- Vast resources (D atoms) - virtually infinite supply in sea water
- Very high energy density ($\times 10^6$ - TNT, Natural gas,...)
- Radioactive byproducts are much lesser/short-lived than from fission
- Requires $> 10^7$ K plasma that needs to be confined/controlled
- Worldwide efforts ($>>\$B$) for over 40y --> ITER / ICF
- Need for breakthrough in fusion induction, control and scaleup
--> Acoustic ICF (Bubble) fusion (Science -3/8/2002)

-Taking \$0.05/lb for natural gas; \$295/lb of D₂O
D₂O is $\sim 6 \times 10^3$ times more expensive; but has $\times 10^6$ more energy
- 2 Trillion dollar world energy market

TEAM MEMBERS

ORNL/PURDUE UNIVERSITY

- Rusi Taleyarkhan (team leader) → Purdue University
- Colin D. West (retd.)

ORAU

- J. S. Cho (Post-Doc)

Rensselaer Polytechnic Institute

- R. T. Lahey, Jr. (NAE, Prof/Dean)
- R. C. Block (Prof./A.Dean, previously of ORNL)

Russian Academy of Sciences

- Robert Nigmatulin (President, Duma member)

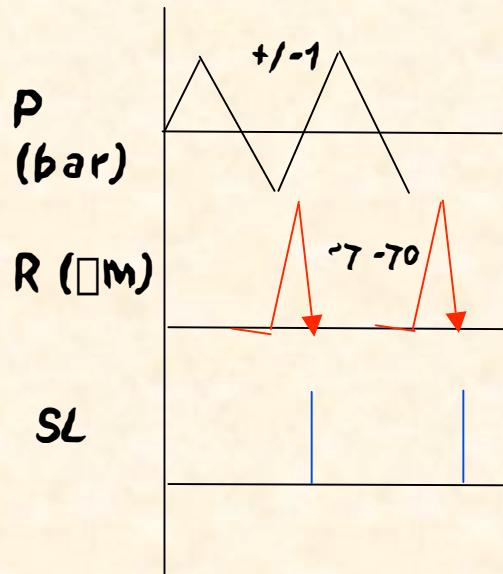
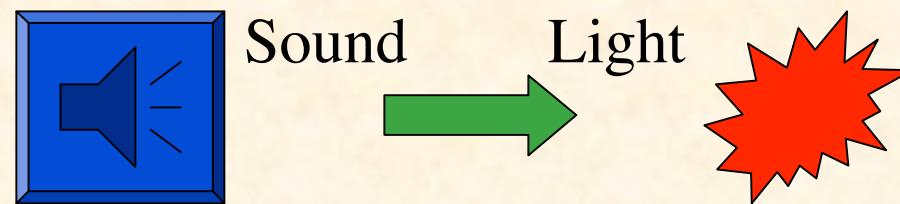
PRESENTATION TOPICS

-Overview of Novel Approach

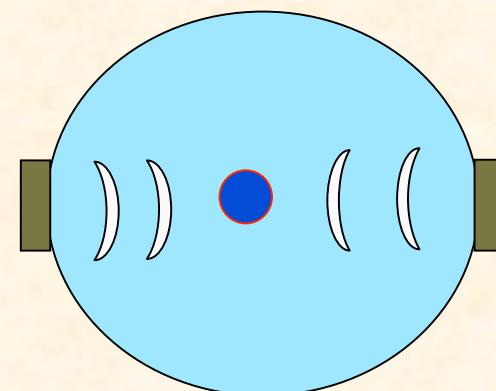
- Experimentation/Analyses & Key Results (3/8/2003 - Science)
- New Results (in response to suggestions for improvement)
 - Intense assessments (over 12 months)
 - Paper released by ORNL President for publication
 - Published in Phys.Rev.E (March, 2004)
- Movies
- Implications / Path Forward
- Challenges / Opportunities

SONOLUMINESCENCE

(Powerful energy concentrator $\sim 10^{11}$)



CONVENTIONAL SBSL



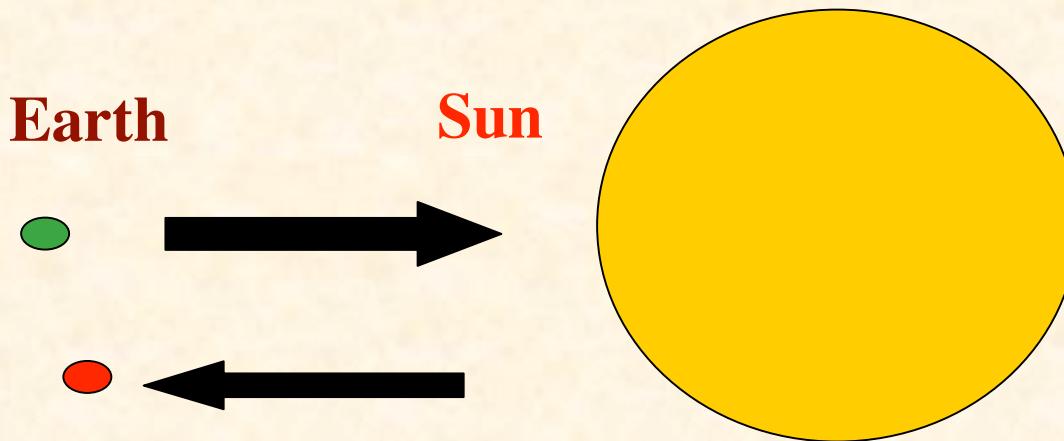
$R_m/R_o \sim 10$

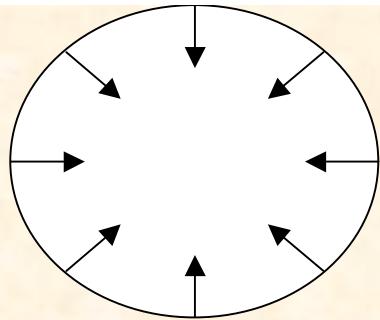
$T_m \sim 100,000 \text{ K}$

Stability Limits

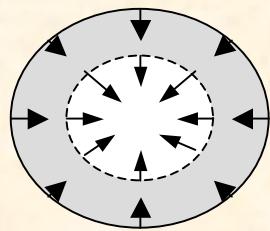
OUR APPROACH

- Choose high \square organic liquid; degassed and at low temperatures
- Stretch liquid like a spring (~ -250 psi)
- Shoot neutrons (10^{-12} mm) & form tiny (~ 50 nm) bubbles
- Grow Really Big (~ 5 mm); **Rm/Ro $\sim 100,000$**
- Implode with trillion times greater energy - vs conventional SBSL)

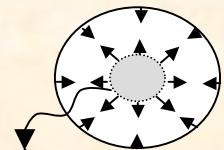




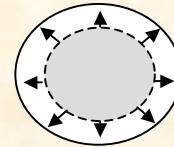
(a)
Start of the Bubble Implosion
(Mach No. <1)



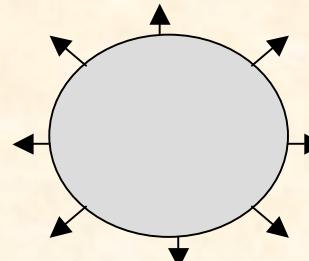
(b)
Shock Wave Formation
(Mach No. =1)



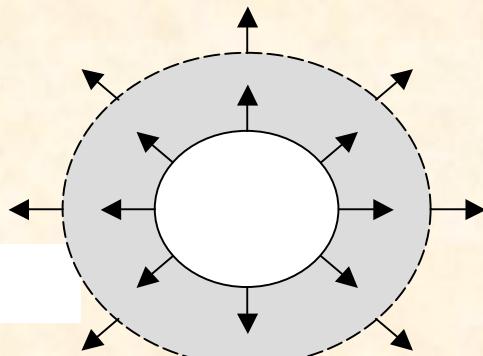
(c)
Shock-Induced
Super-Compression
and
Gas/Plasma Heating



(d)
Shock Reflection,
 $R(t)=R_{\min}$



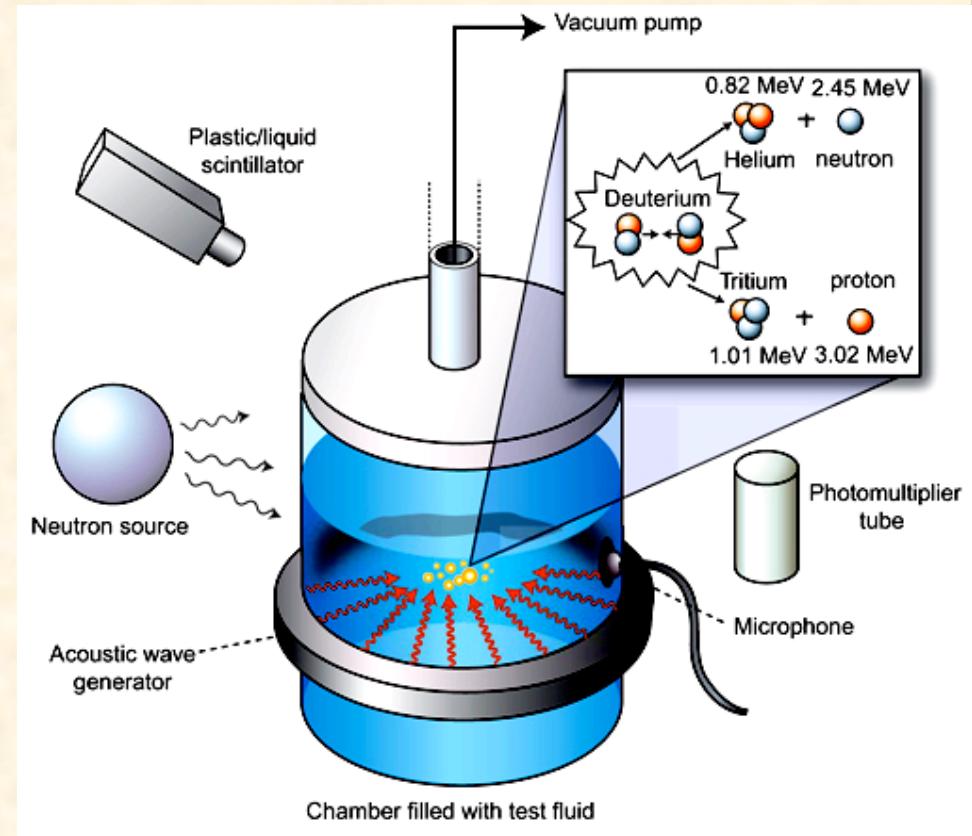
(e)
Onset of
Bubble Expansion

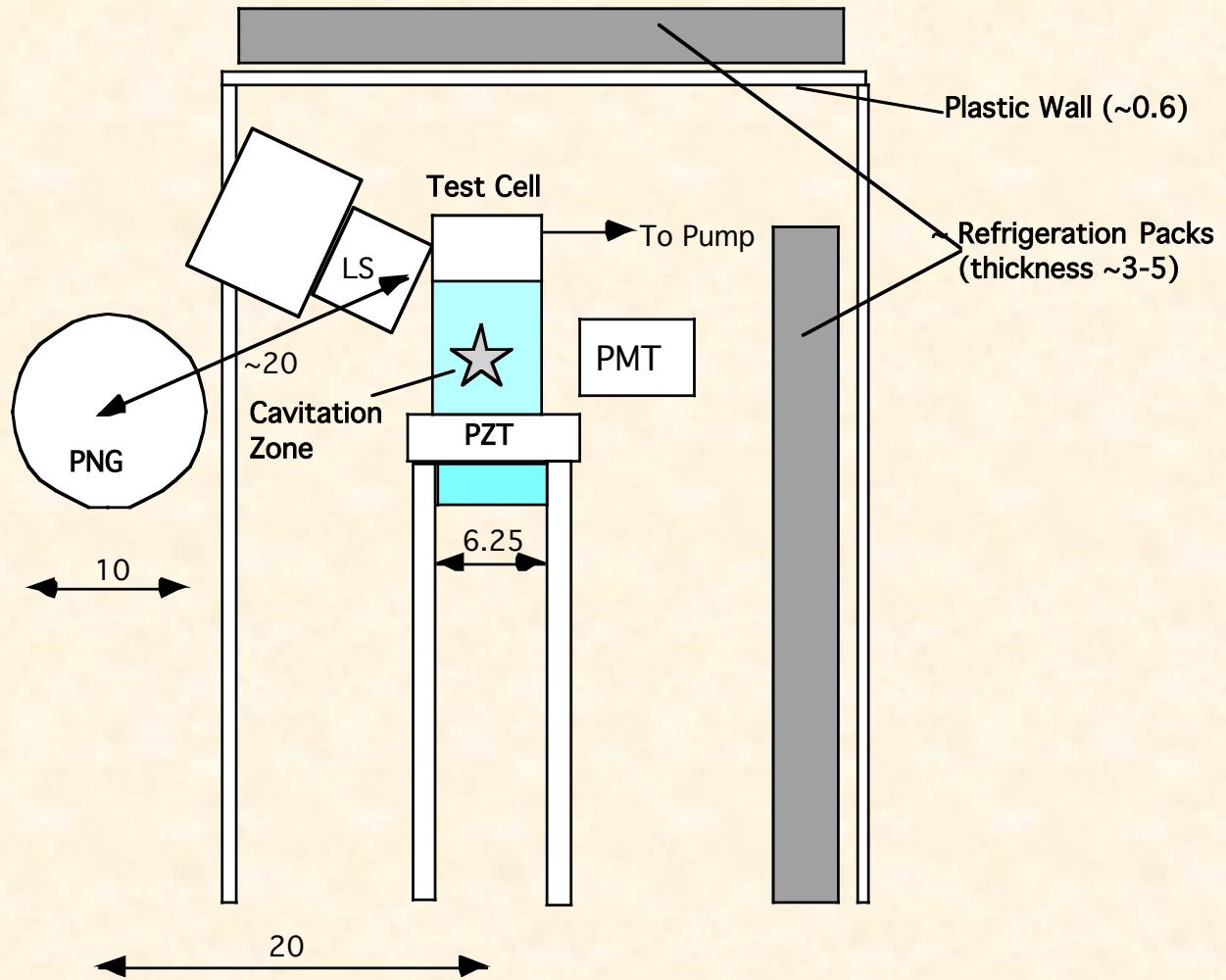


(f)
Shock Wave Formation
In the Liquid

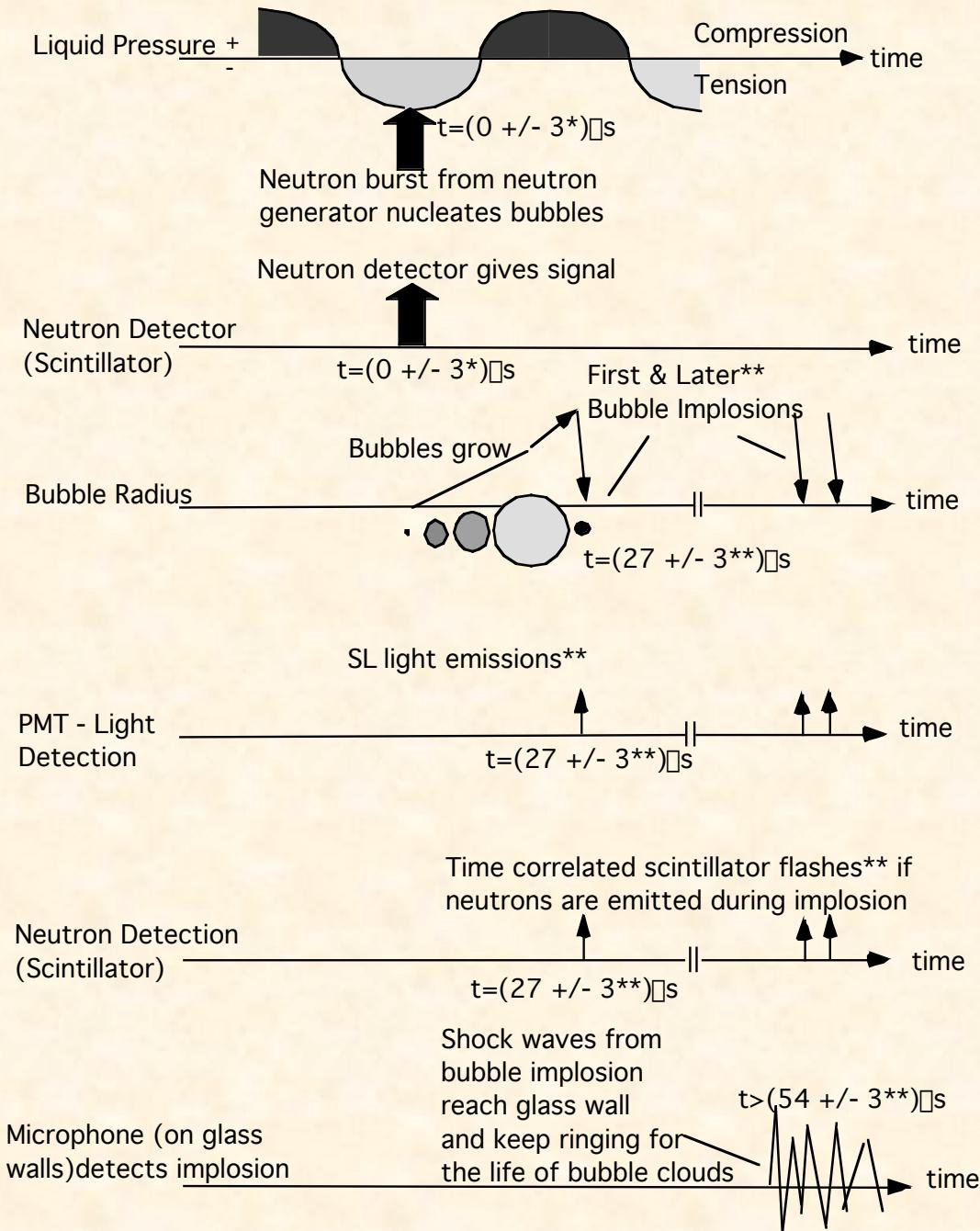
Nuclear fusion in collapsing deuterated acetone bubbles

- Succeed in making large bubbles / clouds, up to 6 mm (from 60nm)
- Get $\sim 10^7$ Kelvin; 10^3 Mbar in gas inside collapsing bubble
- Measure neutrons/tritium

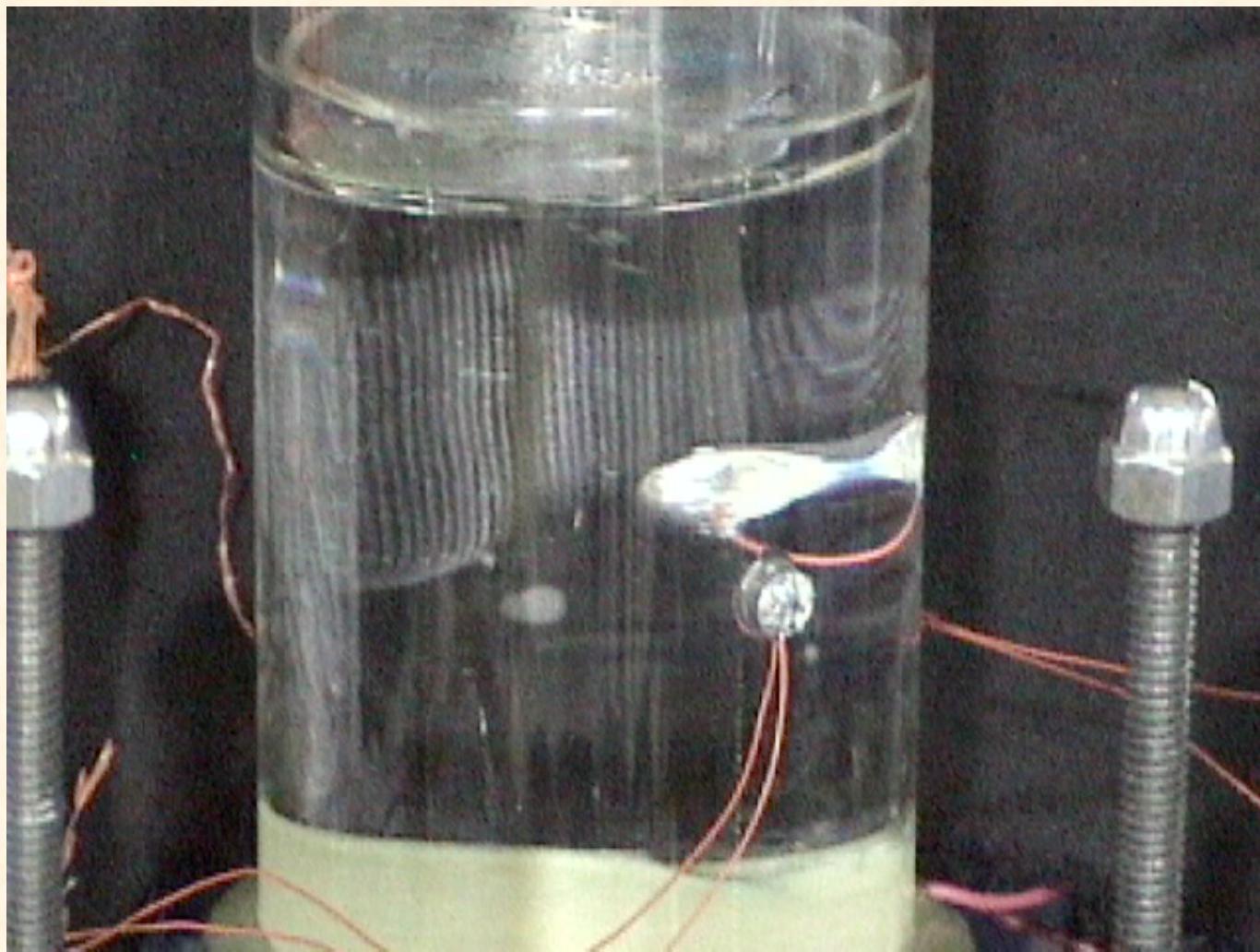




Experimental Sequence of Events



“The Sound of Neutrons”



Rusi Taleyarkhan

NUCLEAR FUSION ?

-Neutrons (of 2.45MeV Energy)?

-Tritium?

-Time Correlation with SL?

- In Line with Theory & Physics ?

- Checked with D-Acetone
& Control Liquid (H-Acetone)?

RANGE OF EXPERIMENTS (3/8/2002-Science)

- System Characterization (test cell development/qualification)
 - The most time consuming step (~2y)
- Tritium Monitoring
- Neutron counts evaluation using pulse-shape-discrimination (PSD)
 - Calibrations with Co,Cs,Pu-Be,PNG
 - Energy of emitted neutrons
- Time correlation of nuclear emissions with SL flashes and shocks

C₃D₆O - Test liquid; C₃H₆O - Control Liquid
Baseline conditions: ~ 0°C, PNG at ~5x10⁵ n/s

TRITIUM MONITORING (3/8/2002-Science)

- **Liquid Scintillation Counting**

- > LS6500 Beckman(baseline); LS5000/Packard (crosschecks)
 - > Ecolite cocktail (15:1); glass vials
 - > Counts in 5-18 keV window (beta emissions from T)

- **Testing with Control Liquid --C₃H₆O (7h and 12h; 0°C)**

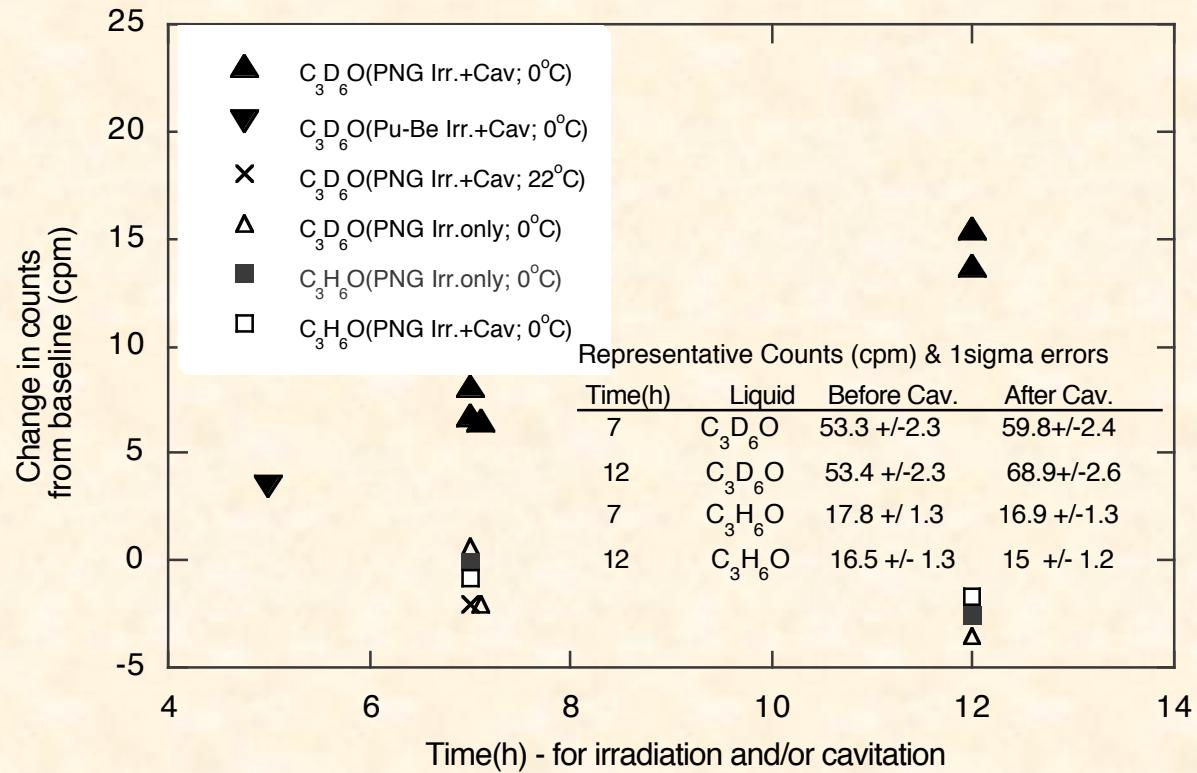
- > PNG only
 - > PNG + Cavitation

- **Testing with C₃D₆O (7h and 12h)**

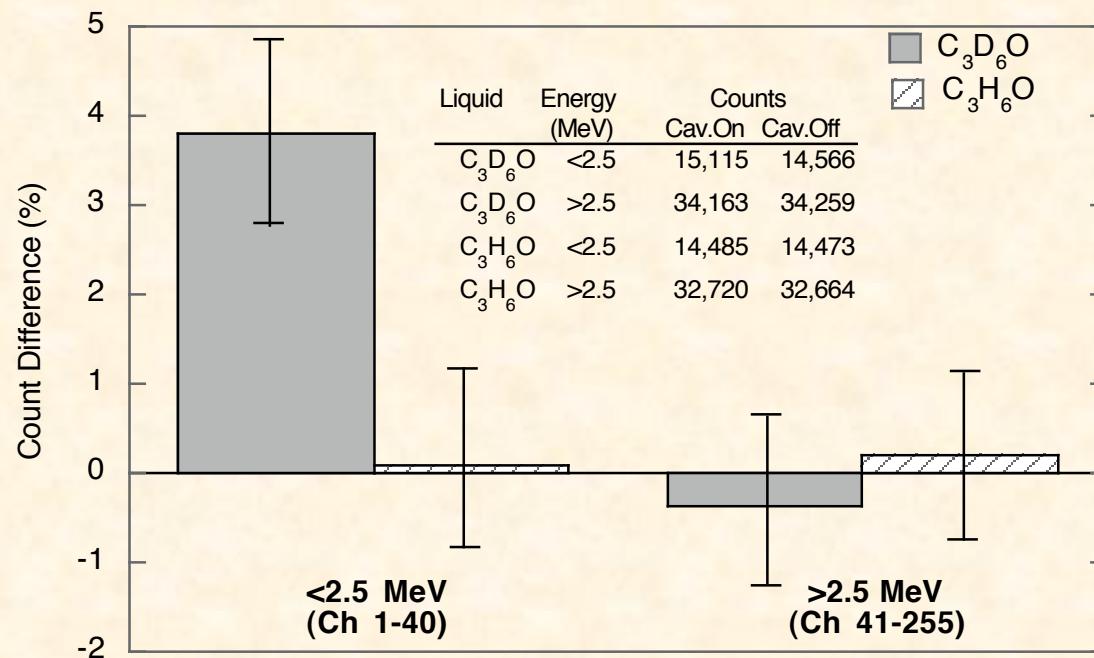
- > PNG only (0°C)
 - > PNG + Cavitation (0°C)
 - > Pu-Be source (5h) --> 0°C
 - > PNG only (20°C)
 - > PNG + Cavitation (20°C)

SUMMARY OF TRITIUM MONITORING RESULTS

(3/8/2002 - Science)

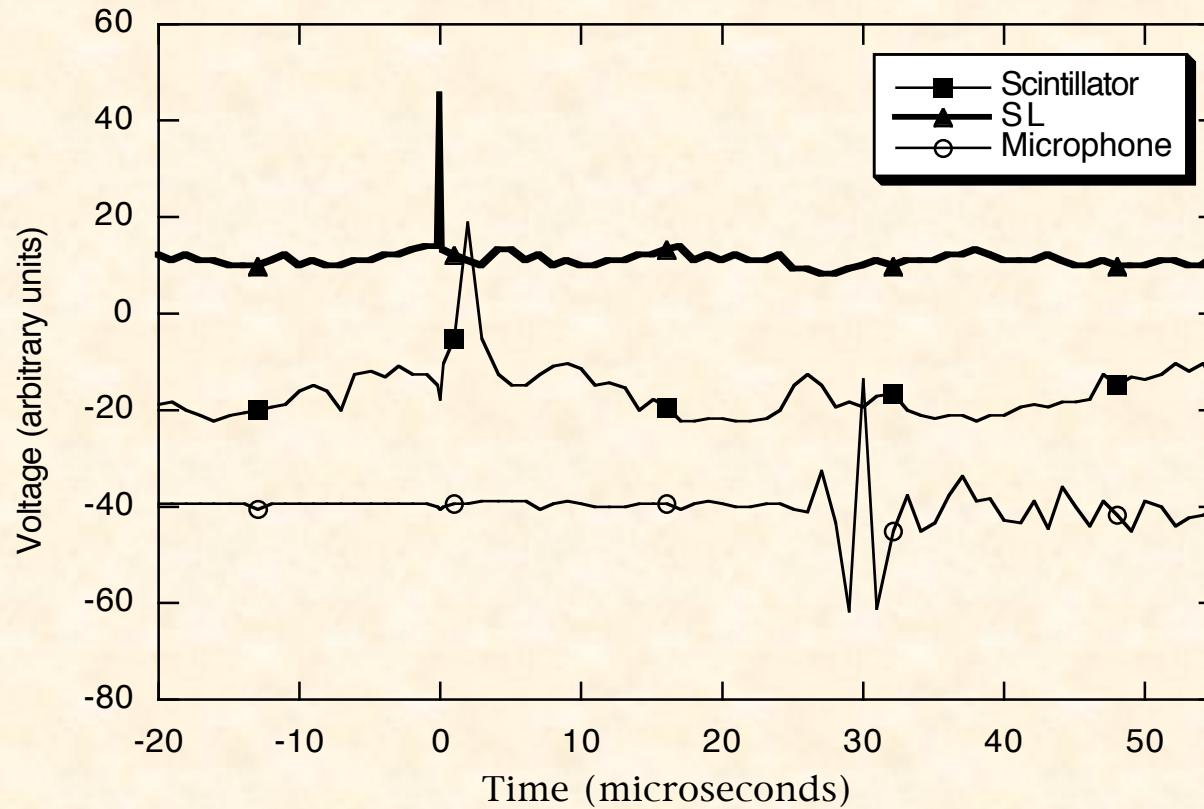


RESULTS OF NEUTRON COUNTING USING PSD



Detector calibrated in-situ with Co,Cs,Pu-Be and PNG Sources

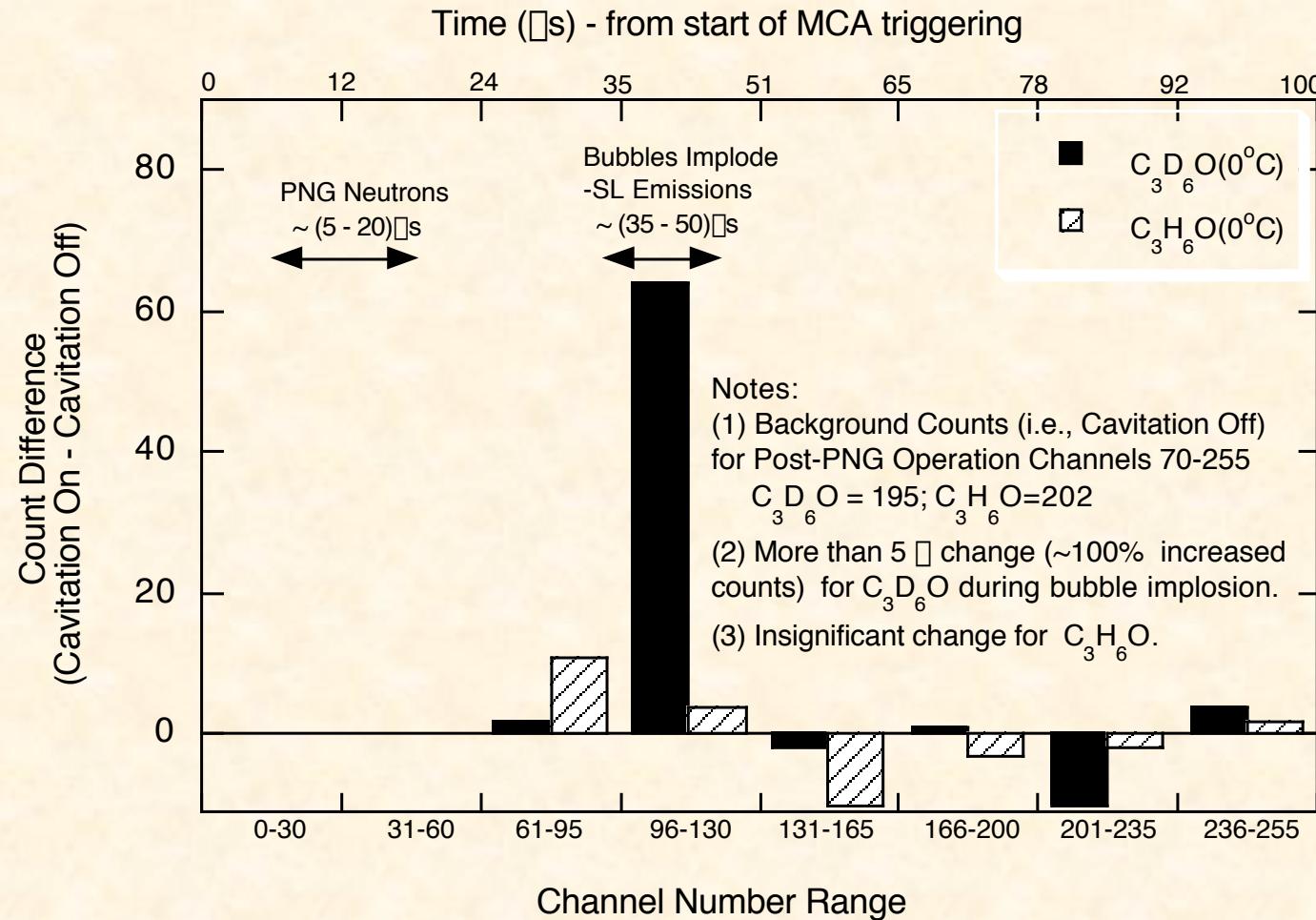
TIME CORRELATION SIGNALS - MODE 1



Such data not observed for $\text{C}_3\text{H}_6\text{O}$ or warm $\text{C}_3\text{D}_6\text{O}$

TIME-CORRELATION DATA - MODE 2

Science (3/8/2002)

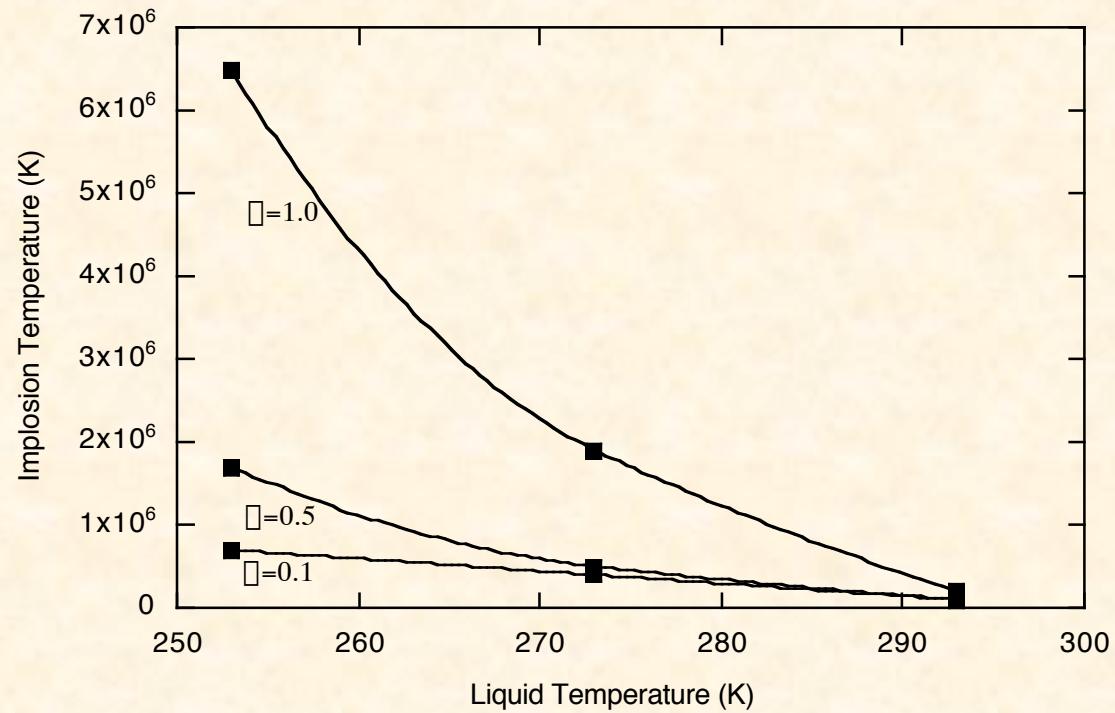


IMPLOSION DYNAMICS MODELING/SIMULATION

- **Two stage modeling --> HYDRO code**
 - Stage 1: Low Mach No. (Rayleigh-Plesset formulations)
 - Stage 2: High Mach No. (Shock modeling; Mie-Gruniesen form of EOS from shock data for acetone)
 - Spatio-temporal neutron generation modeling -LANL D-D data
- **Simulations evaluated the influence of:**
 - Fluid type (low/high ρ)
 - Temperature of operation

IMPLOSIVE COLLAPSE SIMULATION RESULTS OF HYDRO CODE CALCULATIONS

Science (3/8/2002)



EVIDENCE FOR NUCLEAR FUSION

(Science, 3/8/2002)

-**Neutrons (of Correct Energy)?**

YES! --> $\sim 2 \times 10^5$ n/s of 2.5 MeV (~ 3 to 4 SD)

-**Tritium?**

YES! --> $\sim 7 \times 10^5$ n-t/s (~ 5 SD)

-**Time Correlation with SL?**

YES!

- **In Line with Theory & Physics ?**

YES!

- **Checked with D-Acetone & Control Liquid (H-Acetone)?**

- Only for cavitated D-Acetone

- Never for H-Acetone

CONDITIONS FOR NUCLEAR EMISSIONS DURING ACOUSTIC CAVITATION

- Liquid was organic (C_3D_6O) and deuterated
- Drive pressure amplitude $\sim +/- 15\text{bar}$ using a PiezoSystems amplifier tied to a resonant acoustic chamber operating @ $\sim 20\text{ kHz}$.
- Neutrons (14 MeV) nucleated bubble clouds ($\sim 30 - 50/\text{sec.}$)
** No cavitation to occur without neutrons **
- Bubble clouds nucleated when tension is greatest; growth - to $\sim 6\text{mm}$ prior to collapse
- Liquid was degassed; Chamber under $27''\text{Hg}$ vacuum
- Liquid temperature $\sim 0^\circ\text{C}$

Key Comments/Suggestions on Science (3/8/2002) Paper

- Improve neutron-gamma detection statistics & calibration
 - > New detector; Extensive calibrations; x10 efficiency
- Develop better understanding of emissions through entire portion of bubble cloud lifetime (nucleation through re-dissolution)
 - > High-speed imaging; Multi-channel time spectra
 - > SL, Gamma & Neutron gated spectra over bubble lifetime
- Address the potential of chemical effects on tritium measurements
 - > Acoustic horn experiments
 - > Re-confirmation of T emission from n-induced cavitation

SYSTEM CHARACTERIZATION

(bubble cloud nucleation to collapse takes $\sim 5\text{ms}$)



0msec

1msec

2msec



3msec

4msec

5msec

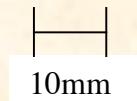
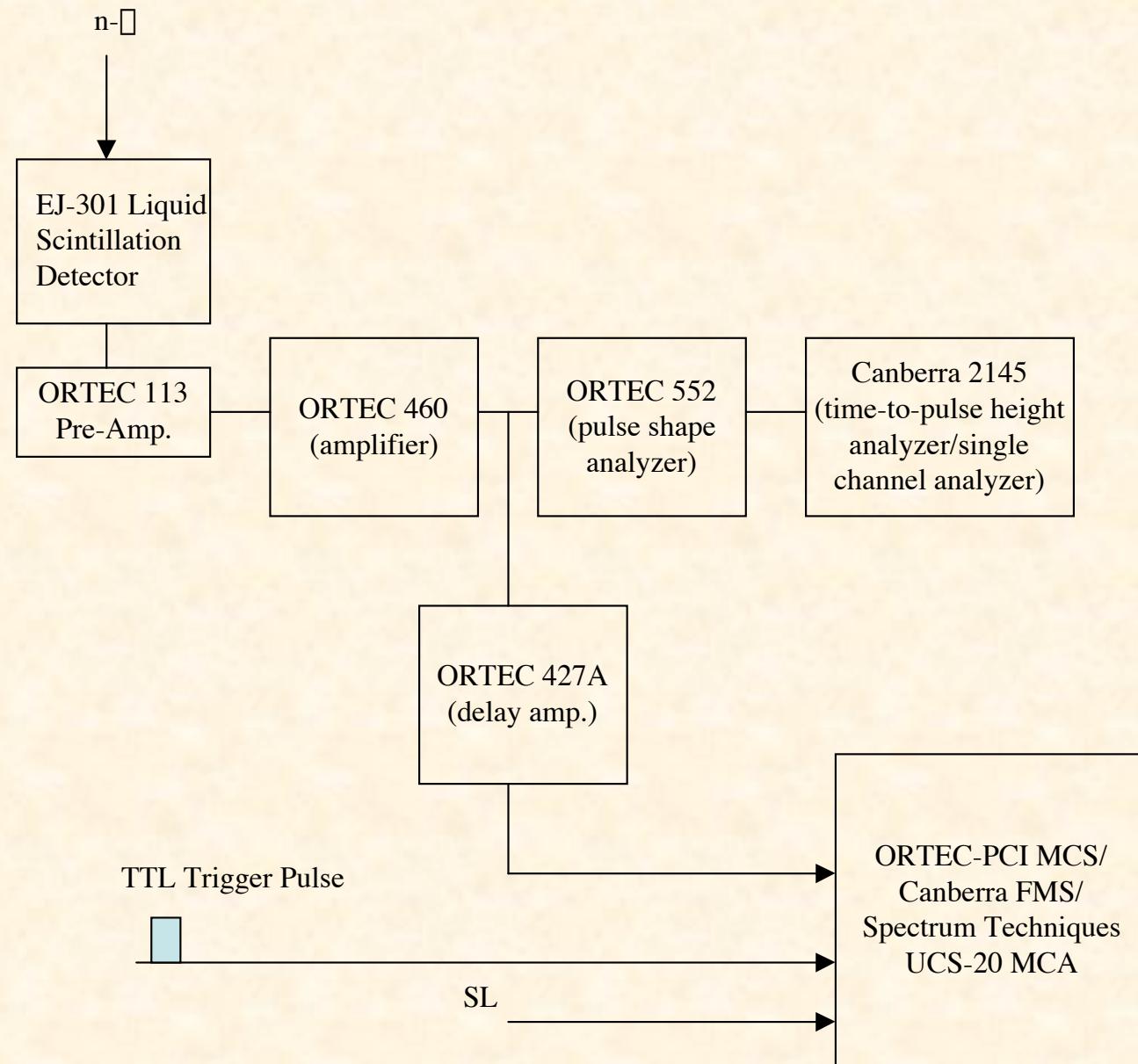


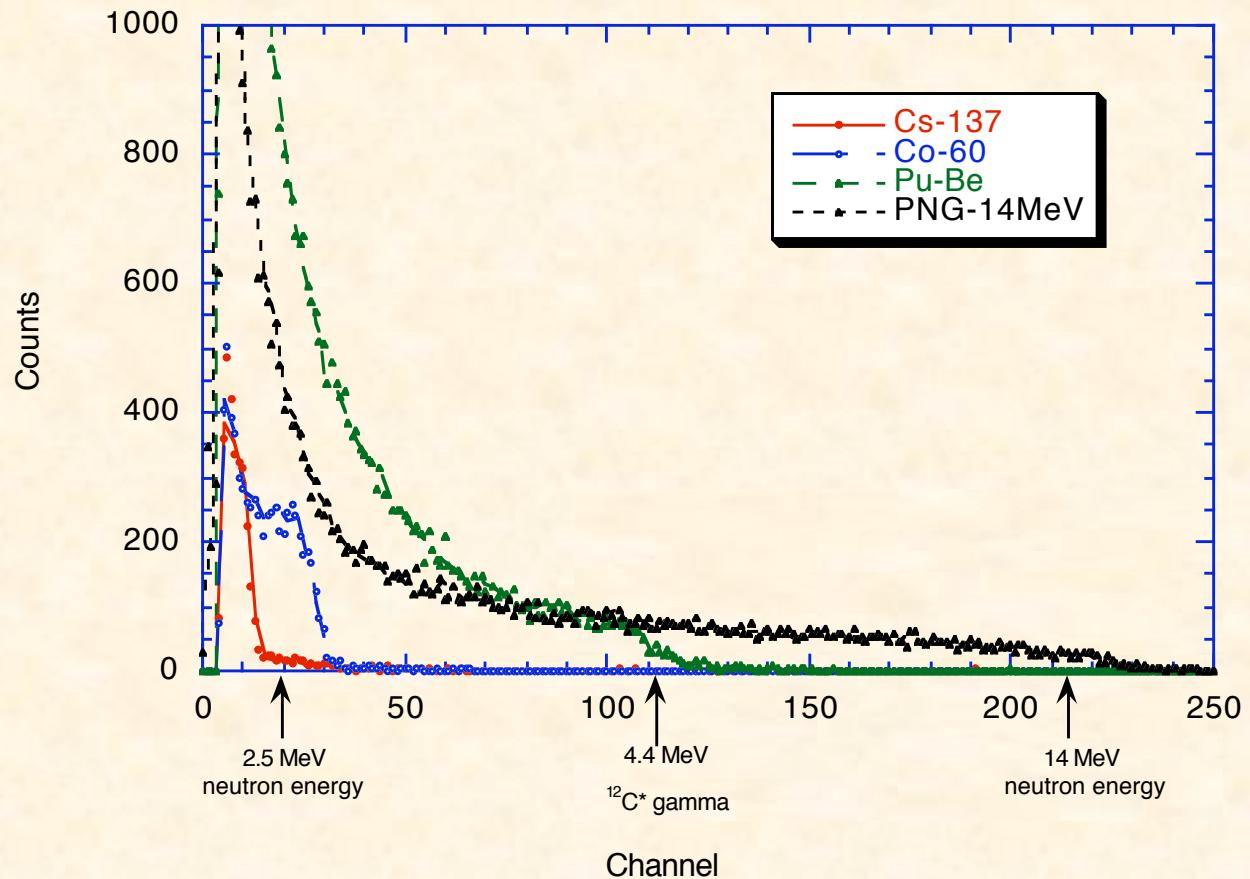
Table 1. Comparison of New Work/Results with Phase 1 Work (3/8/2002, Science Paper)

| Item | New Work with LS Detector | Phase 1 (3/2002 Science paper) |
|---|---|--|
| Detector Liquid/System | EJ-301 (similar to NE-213) 100cc liquid scintillation (LS) detector → Recommended size for PSD | NE-213 based detector made by Elscint; 100cc; → Recommended size for PSD |
| Detector Age | New | > 15y (not recently purged) |
| Electronic component modules | Newly purchased from Ortec | Mixed (some 15+y) |
| Data acquisition via | 1000 time channels (0 to 5,000 μ s between sweeps), MCAs, and scopes; ** Full duration DAQ (including PNG neutron time frame) ** | MCA (0 to 100 μ s), scopes |
| Neutron detection efficiency (ϵ) (Pu-Be) | $X (\sim 6 \times 10^{-4})$ | $\sim < X / 10$ |
| Lower limit for neutron detection | ~ 0.7 MeV ** exp. dependence of ϵ vs E_n ** | ~ 2.0 to 2.1 MeV |
| Gamma ray saturation effects | None/negligible | None/negligible |
| Calibration | 14 MeV, Pu-Be, Co, Cs and RPI's Linac (TOF) | 14 MeV, Co, Cs, Pu-Be; Severe degradation of ϵ at/below Cs line. |
| Reaction chamber | Newly fabricated | Newly fabricated |
| Neutrons measured? | Yes ($\sim 3 \times 10^5$ n/s); 2.5 MeV; $\sim 100\%$ above 14 MeV background and time correlated with SIs) | Yes ($\sim 10^5$ n/s); 2.5 MeV $\sim 4\%$ above 14 MeV background; time correlation data only for first collapse (0 to 100 mic.sec). |
| Tritium data obtained with C_3H_6O / C_3D_6O ? | Yes (~ 3 to 5×10^5 T/s) | Yes ($\sim 7 \times 10^5$ T/s) |
| Acoustic horn cavitation expts. To dismiss chemistry effects (false b counts in 5-18 keV range)? | Yes | No |
| SL emission rates measured (SLs/s) | 30 to 40 | Not measured over entire sweep |
| Gamma ray emissions measured? | Yes (~15 to 20% of 3×10^5 D-D neutron emissions) | No |
| Time correlations measurements over entire duration of emissions | Yes | No (only for first 100 mic.sec) |
| Control experiments with C_3H_6O ? | Yes | Yes |



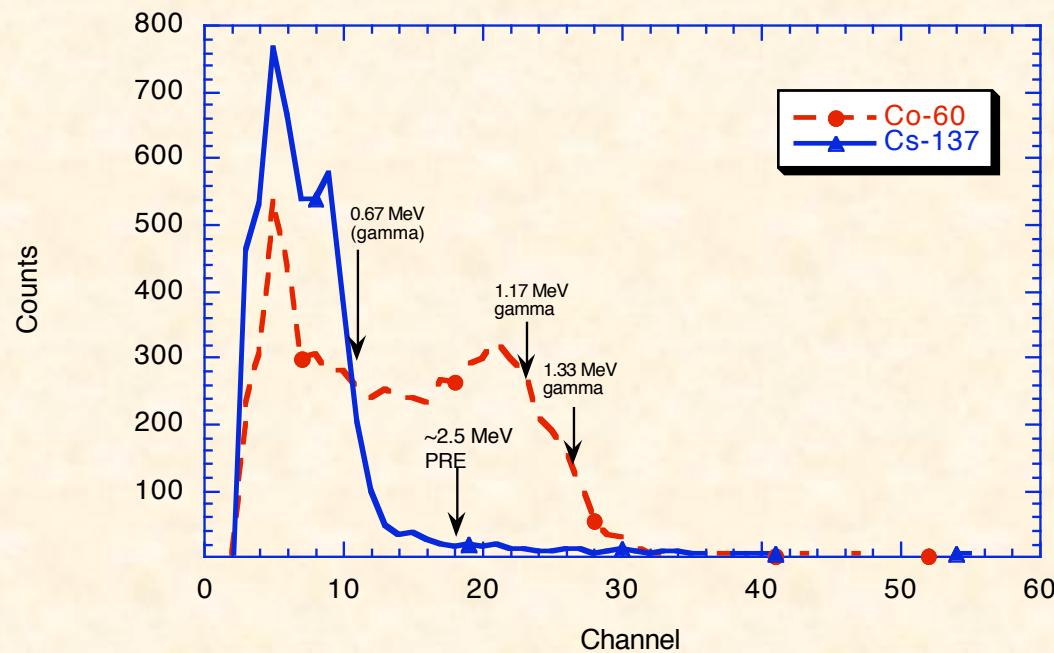
NEW LIQUID SCINTILLATION (LS) DETECTOR

(Extensive Calibrations: Linac TOF, Pu-Be,Co,Cs,PNG)



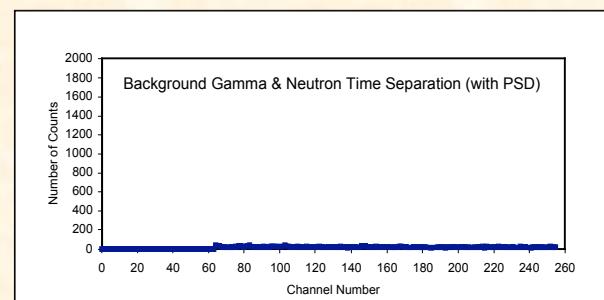
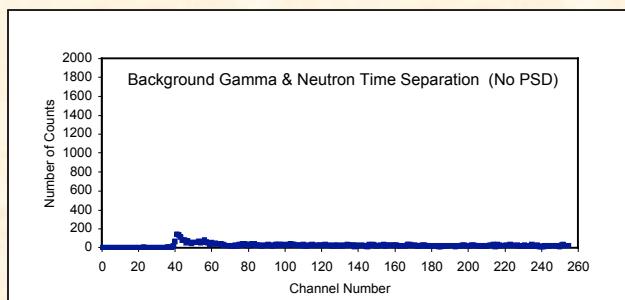
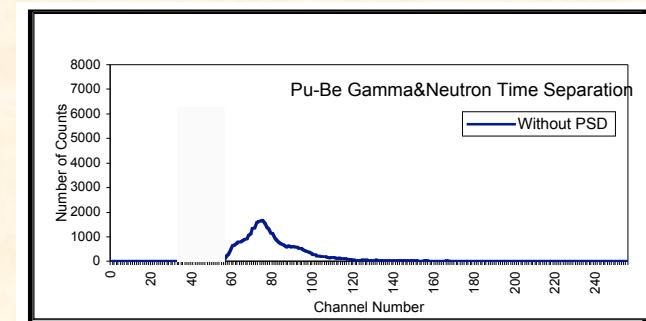
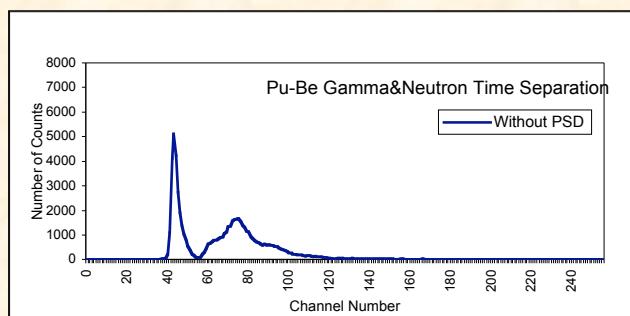
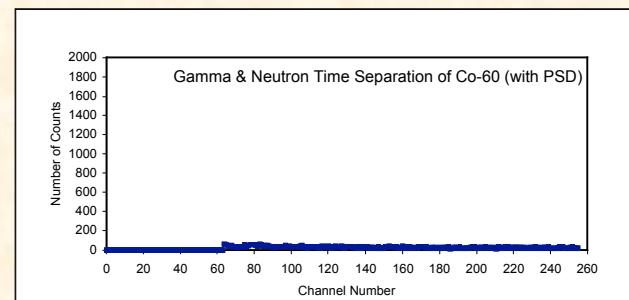
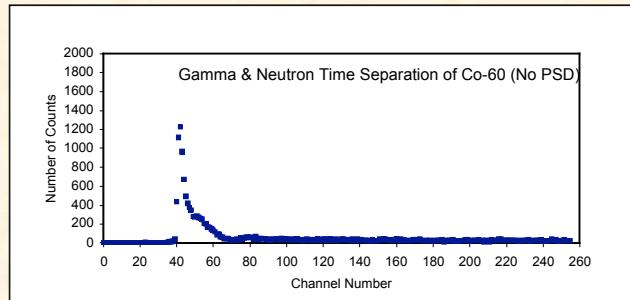
NEW LIQUID SCINTILLATION (LS) DETECTOR

(Extensive Calibrations: Linac TOF, Pu-Be,Co,Cs,PNG)

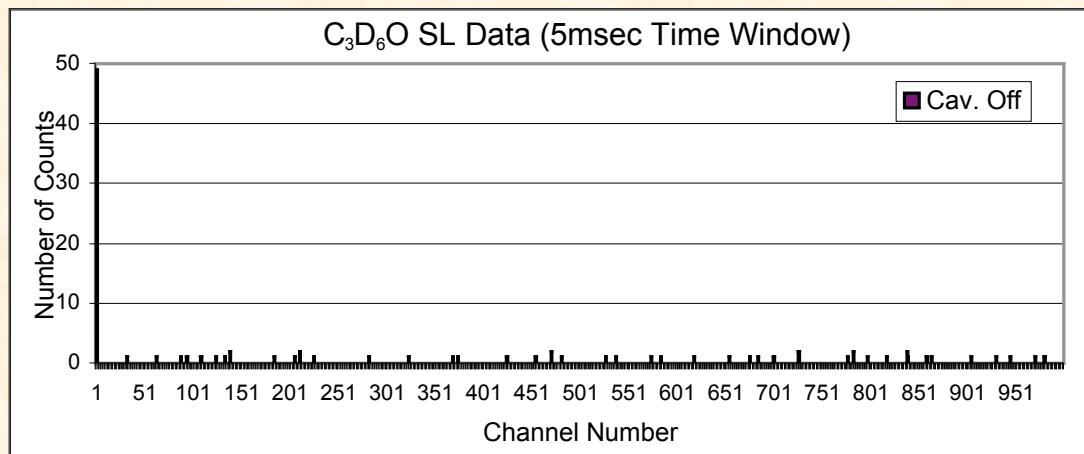
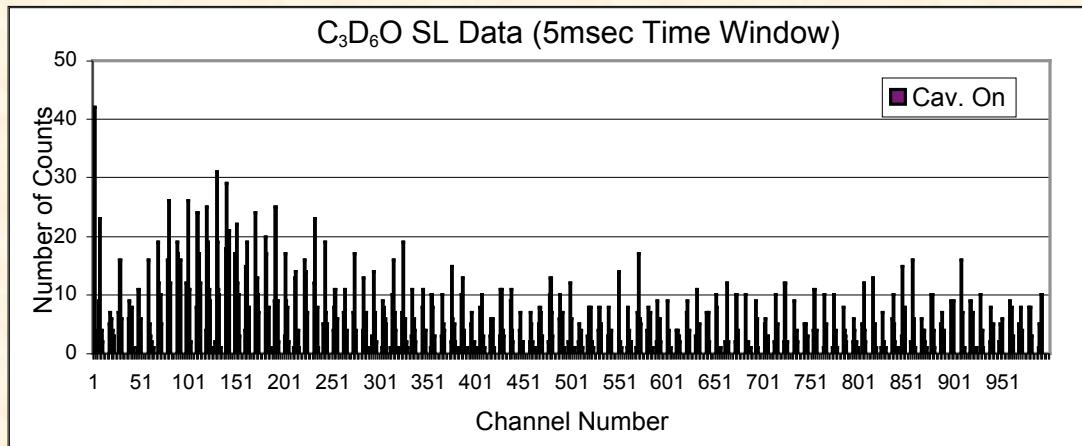


NEW LIQUID SCINTILLATION (LS) DETECTOR

(Conservative Pulse Shape Discrimination)

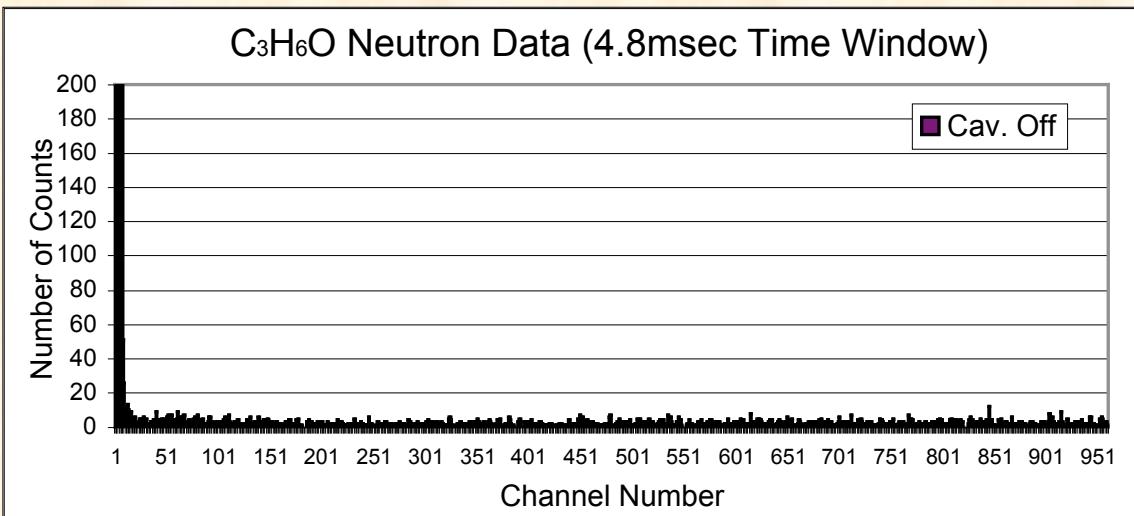
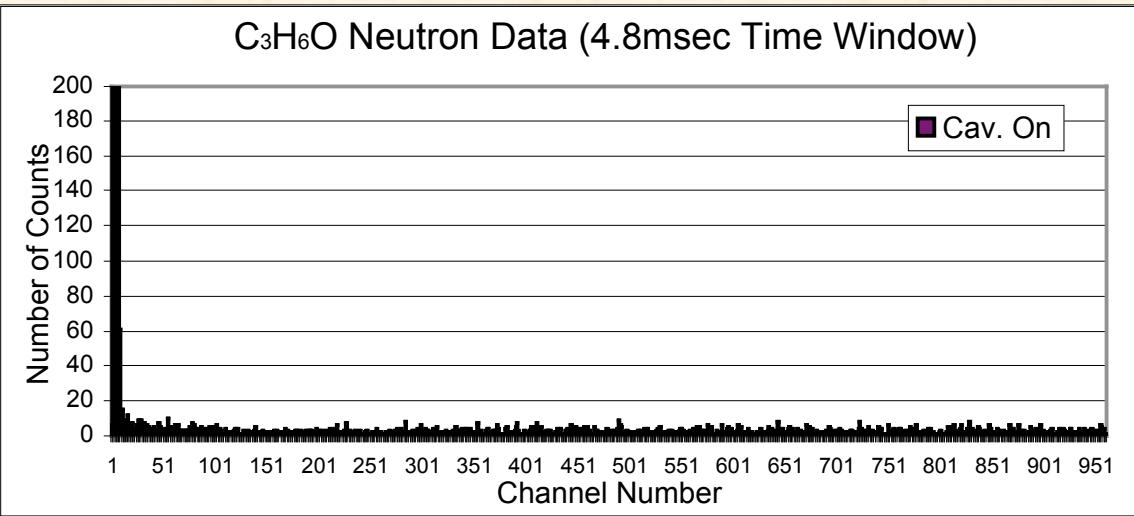


SL TIME SPECTRA (0 to 5000 mic.sec.)



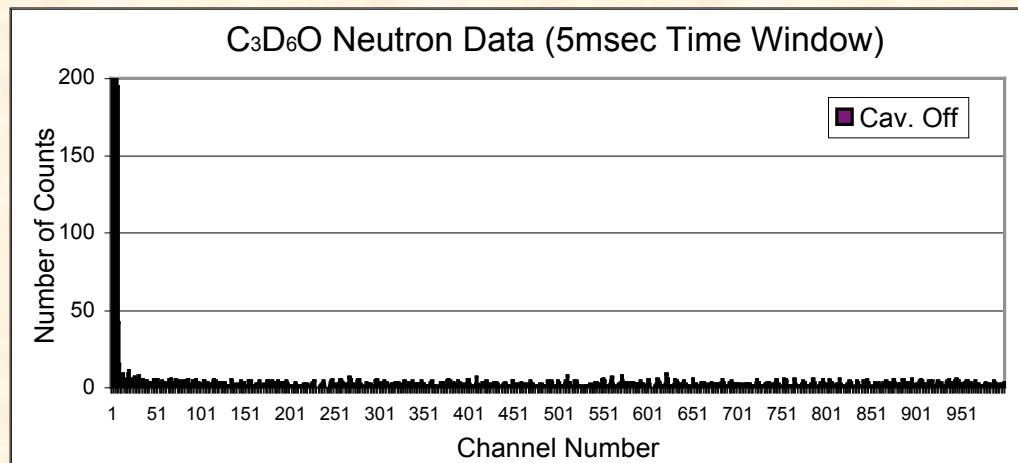
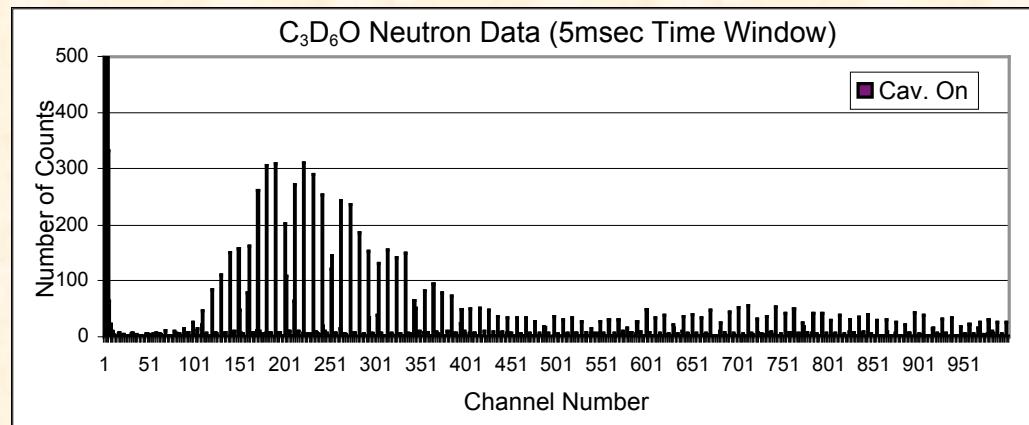
NEUTRON TIME SPECTRA (0 to 5000 mic.sec.)

$\text{C}_3\text{H}_6\text{O}$ ($\sim 0^\circ\text{C}$)



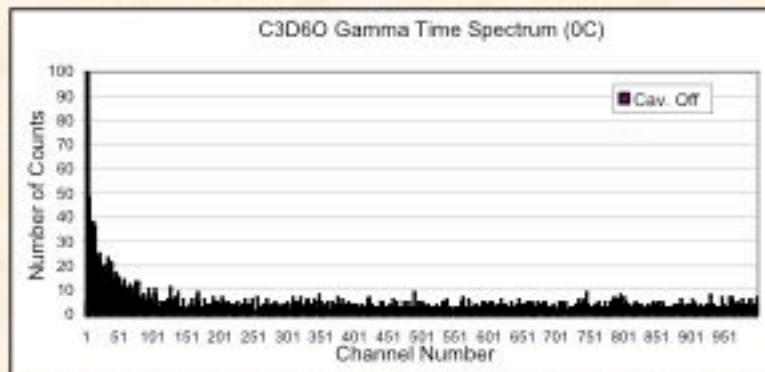
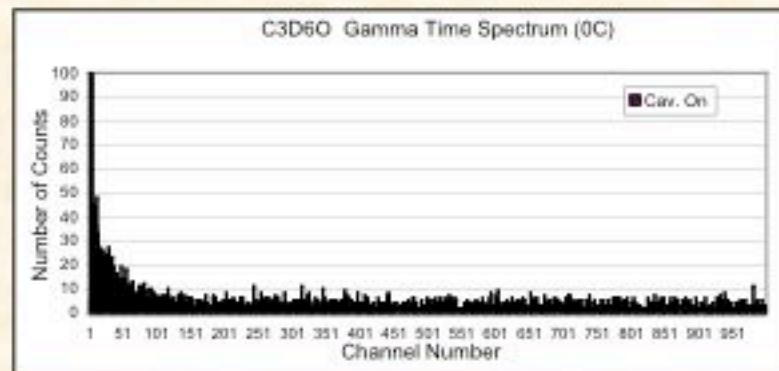
NEUTRON TIME SPECTRA (0 to 5000 mic.sec.)

$\text{C}_3\text{D}_6\text{O}$ ($\sim 0^\circ\text{C}$)



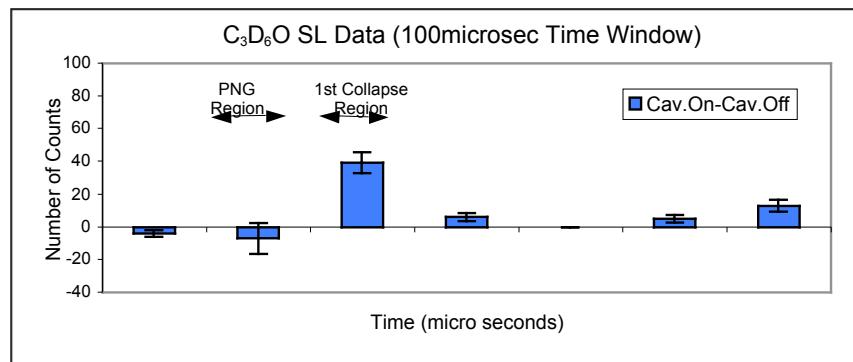
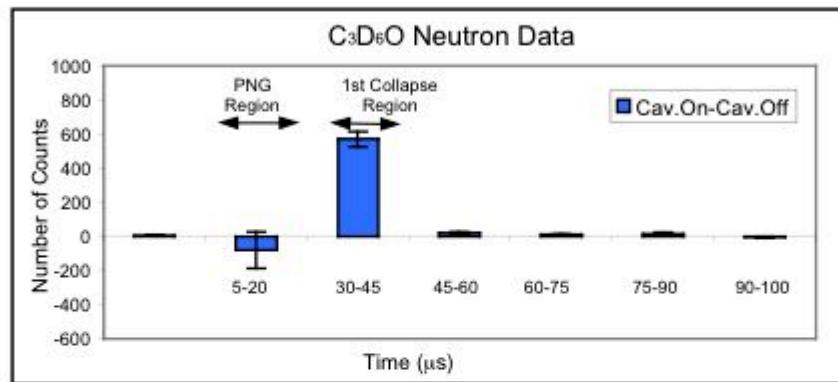
GAMMA TIME SPECTRA (0 to 5000 mic.sec.)

$\text{C}_3\text{D}_6\text{O}$ ($\sim 0^\circ\text{C}$)

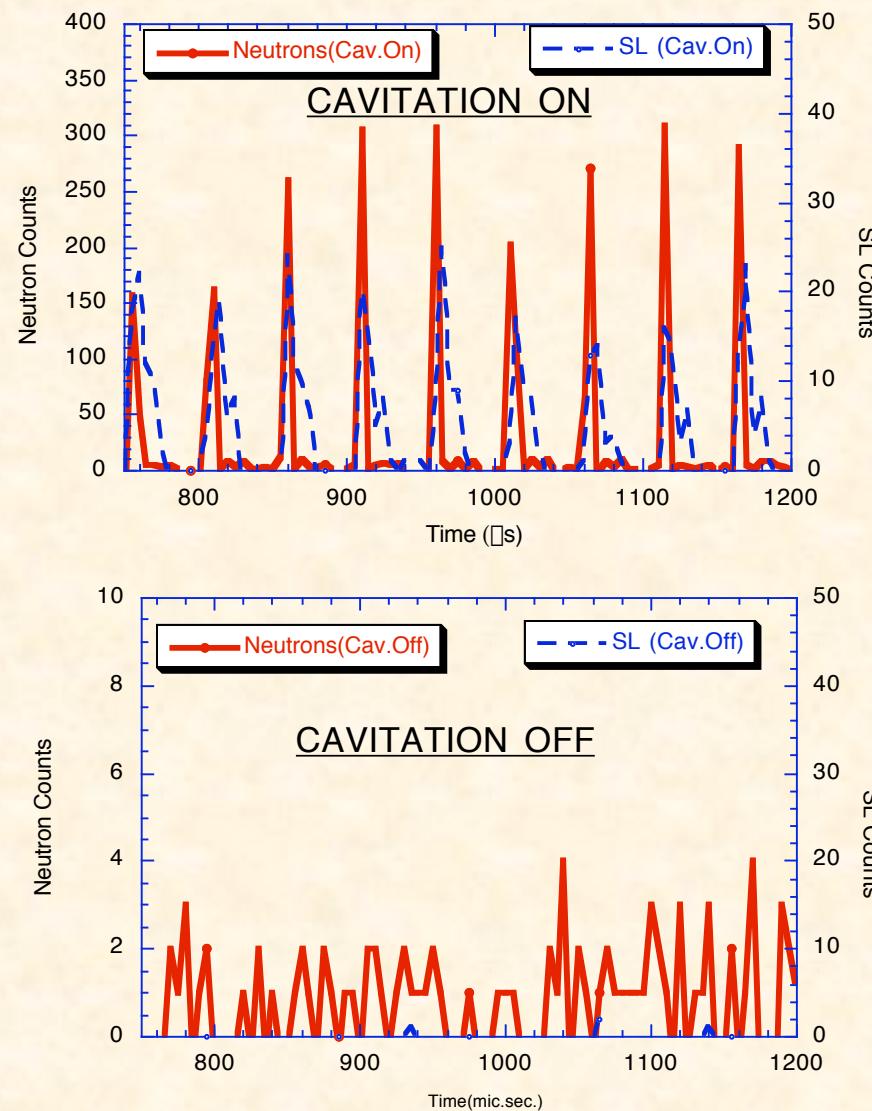


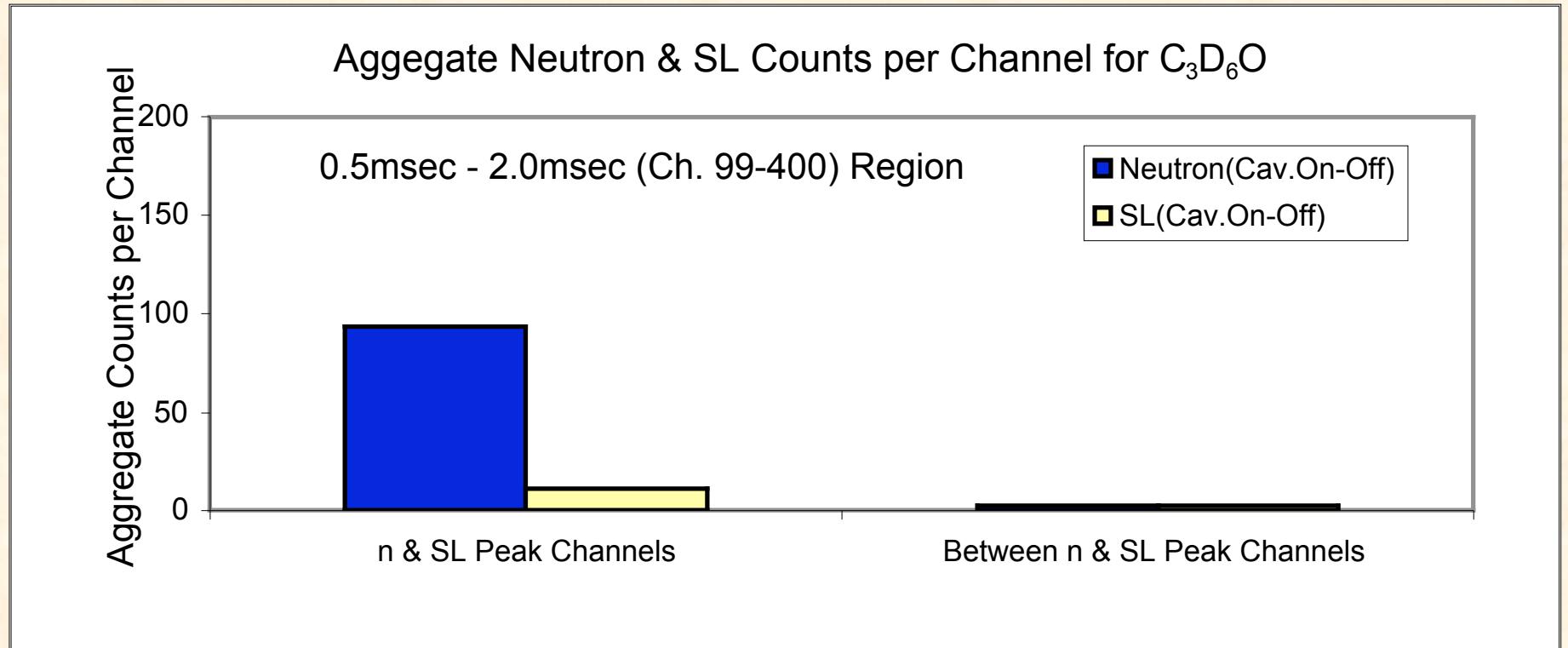
NEUTRON & SL TIME SPECTRA (0 to 100 mic.sec.)

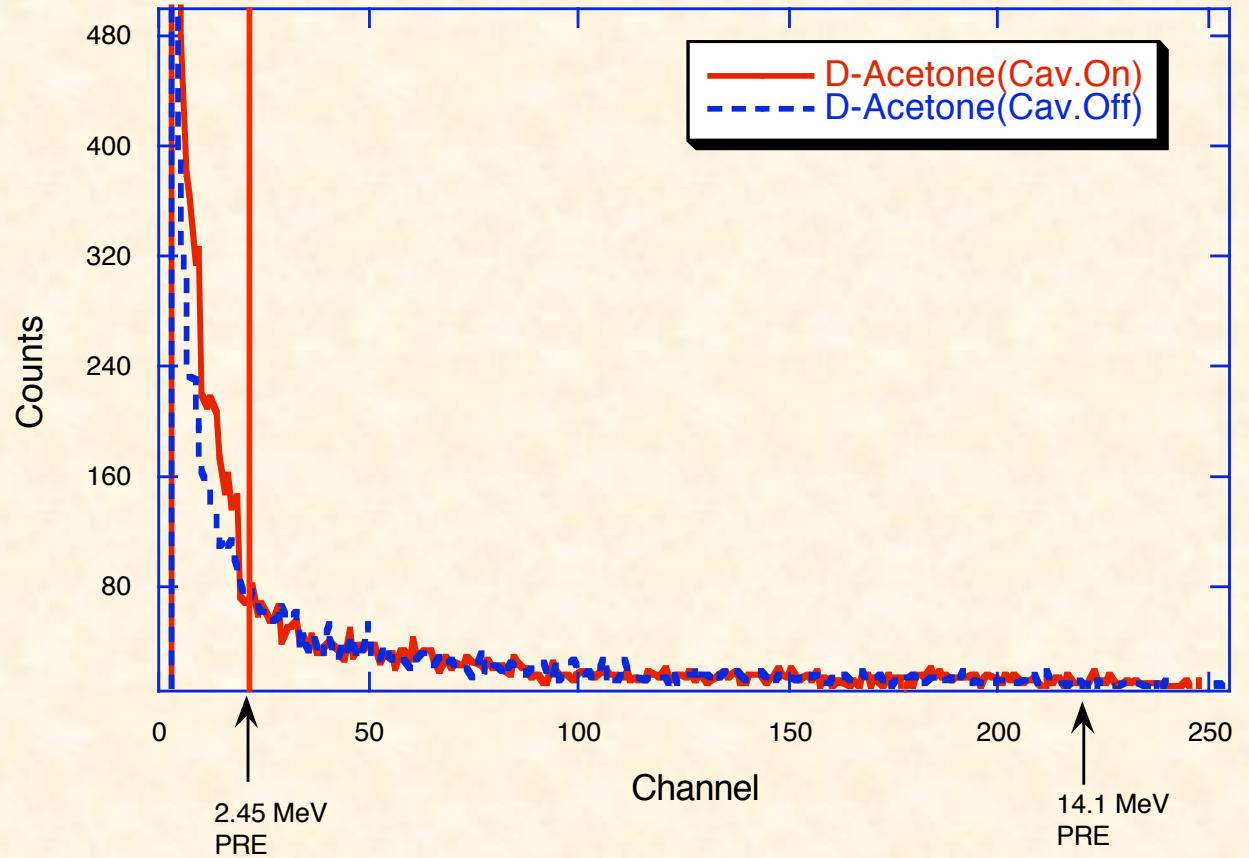
C₃D₆O (~0°C)

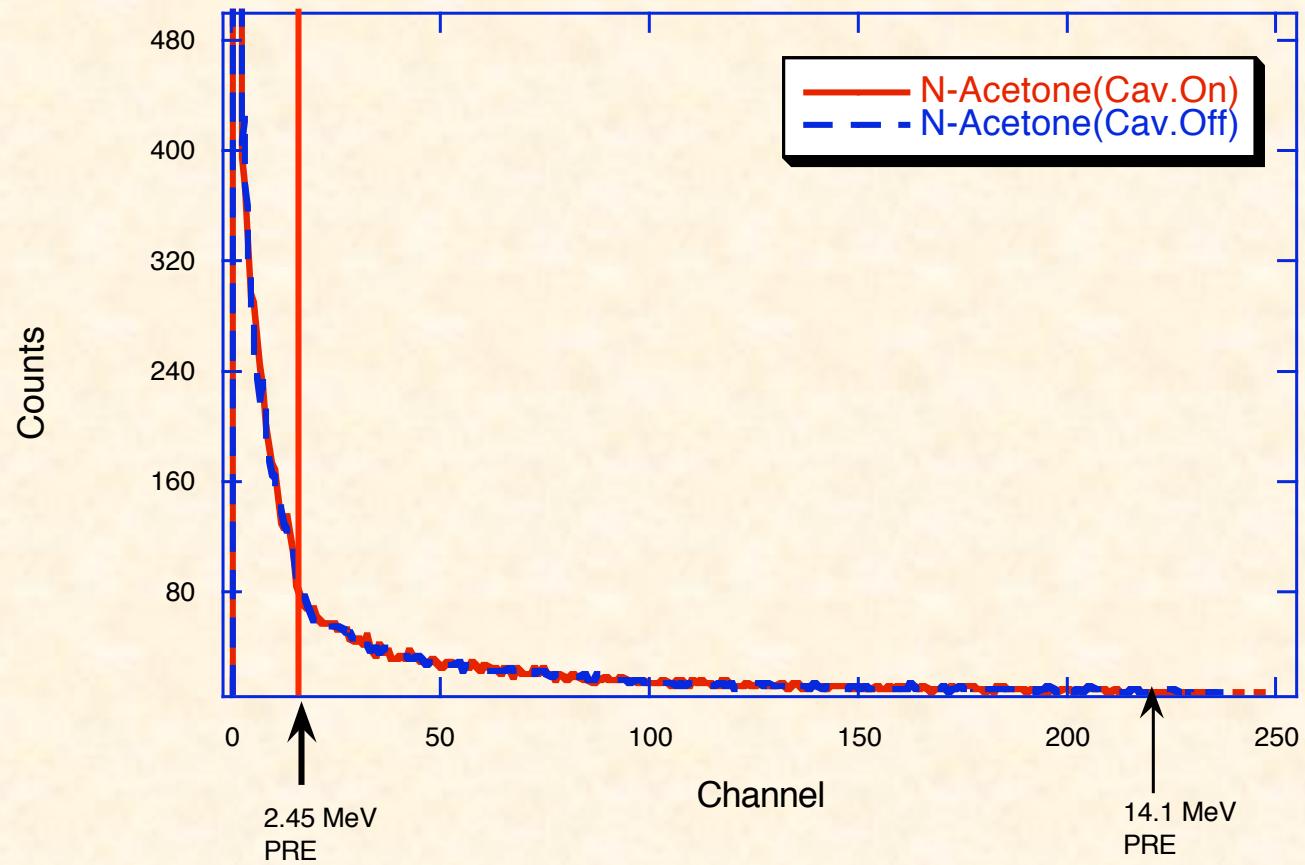


SL-Neutron Time Correlation Spectra ($\text{C}_3\text{D}_6\text{O}$; 0°C)



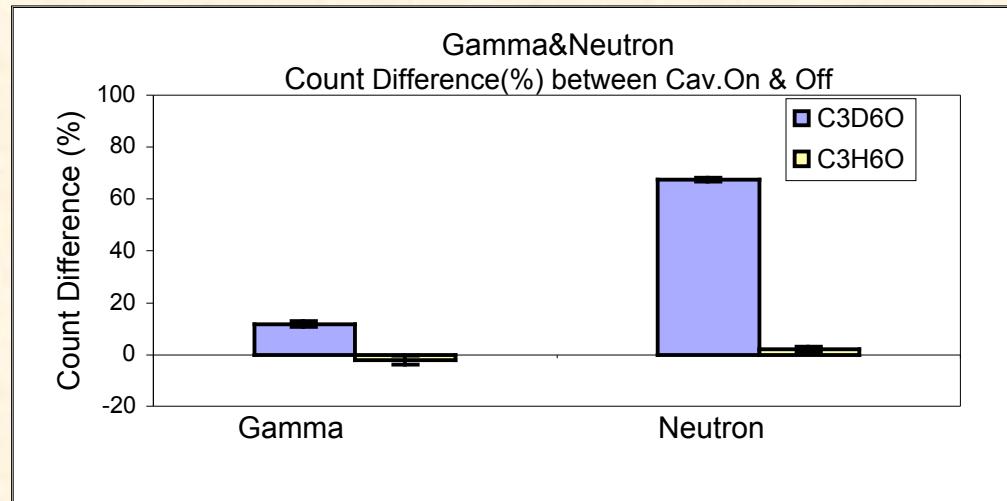




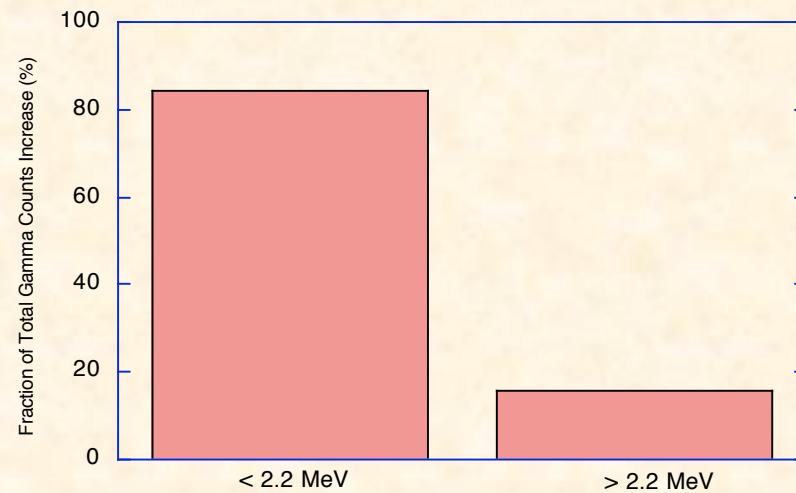


Neutron vs Gamma Changes ($\text{C}_3\text{D}_6\text{O}$, $\text{C}_3\text{H}_6\text{O}$; 0°C)

Gamma emissions ~ 10-15% of neutron emissions -->for $\text{C}_3\text{D}_6\text{O}$



Gamma emissions are largely 2.2 MeV



ACOUSTIC HORN CAVITATION TEST RESULTS

Purpose:

Additional confirmation that conventional cavitation can not result in false indications of low-level beta activity (in the 5-18 keV window)

** Note: already proven - PNG cavitation with $\text{C}_3\text{H}_6\text{O}(0^\circ\text{C}, 20^\circ\text{C})$ and $\text{C}_3\text{D}_6\text{O}(20^\circ\text{C})$

Acoustic Horn Testing:

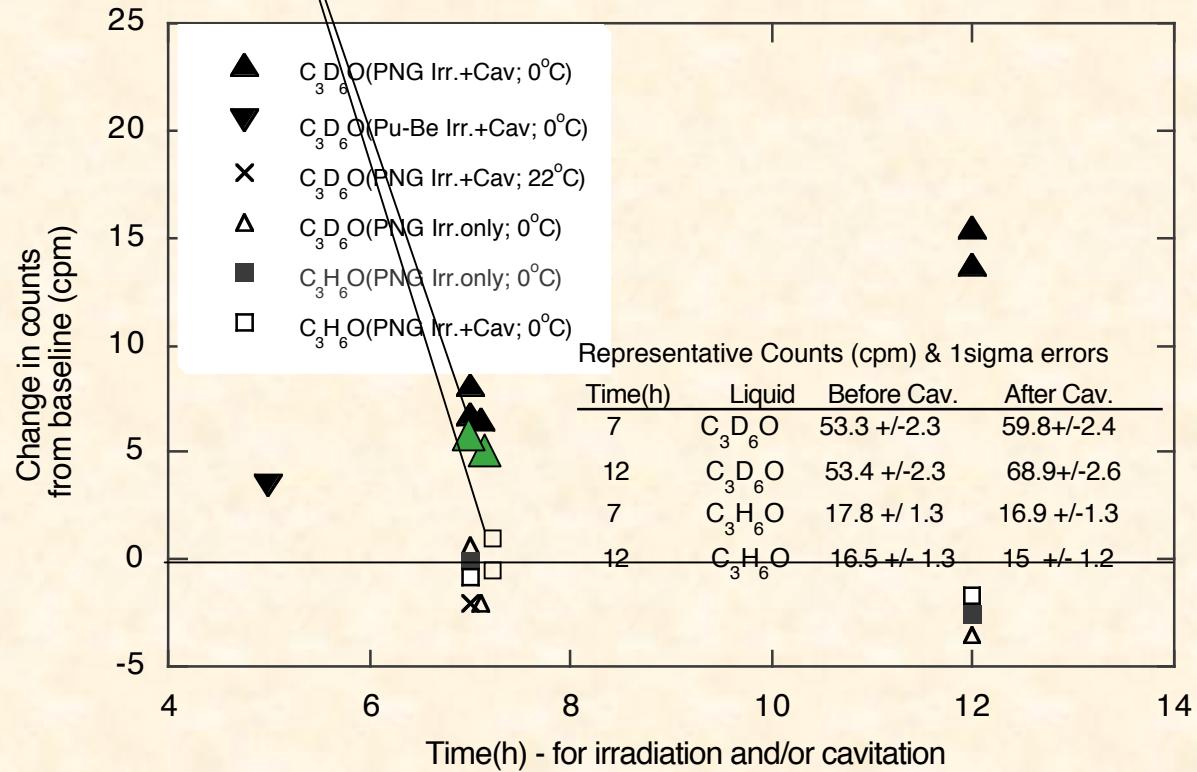
Used high-powered horn (700W@ ~40-50% power level, 20kHz)
Tested with chilled $\text{C}_3\text{H}_6\text{O}$ and $\text{C}_3\text{D}_6\text{O}$ -- see video

Results indicate negligible changes:

Changes in tritium counts:

- ~ 0.1 cpm (1 SD ~3 cpm) for $\text{C}_3\text{D}_6\text{O}$
- ~ 1.0 cpm (1 SD ~2 cpm) for $\text{C}_3\text{H}_6\text{O}$

CONFIRMED TRITIUM GENERATION (New Chamber)



-Beckman LS6500 & LS5000 calibrated counters (5-18 keV);
 -Ecolite - Scintillation Cocktail (15:1)

NOTE

FOR EVERY EXPERIMENT CONDUCTED

WITH C₃D₆O

WE CONDUCTED A CONTROL EXPERIMENT

WITH C₃H₆O

NEW DATA SUMMARY

- $\sim 3-5 \times 10^5$ n/s of 2.5 MeV Neutron emissions
 - Compatible with tritium output
 - Neutrons time-correlated with SLs over entire 5,000 mic.sec. lifetime
 - Neutrons accompanied with ~ 2.2 MeV gamma rays
 - Gamma emissions $\sim 12-15\%$ of neutron emissions --(Between n peaks)
 - Tritium emission results re-confirmed.
- OBTAINED ONLY for C_3D_6O with n-seeded Cavitation On;
Not when Off & Never for C_3H_6O with or without Cavitation
- Intense acoustic horn cavitation shows no effect on T measurement
 - Effects from cavitation have no significant contributions in the 5-18 keV window

INTENSIVE INTERNAL-ORNL REVIEWS OVER 8 MONTHS

(Selected Reviews / Outcomes)

| <u>Individual</u> | <u>Affiliation</u> | <u>Range of Involvement / Outcome</u> |
|-------------------|----------------------------|--|
| L. Riedinger | ORNL (Dep.Lab. Dir) | Personally directed ORNL internal review team (3 months); approved paper for journal release; Audit; Issued ORNL Position Statement and Summary of Findings |
| G. Young | ORNL (Dir.Phys) | Co-ordinated ORNL-wide in-depth technical reviews; Audit; over 2-3 months; Found nothing technically wrong- input to Lee Riedinger's summary statement |
| J. Harvey | ORNL (Nucl.Phys.) | Laboratory methods / equipment examination; data examinations and paper reviews over 2-4 months -found nothing technically wrong; recommends publication |
| L. Miller | UTK(Nuc.Eng.) | Laboratory equipment, data & paper review ** finds nothing technically wrong ** |
| W. Bugg | UTK/SLAC (Nucl.Phys) | Lab. Visit, data & paper review ** finds nothing technically wrong; recommends self-nucleation expts. |
| M. Embrechts | RPI /LANL (Fusion Eng.) | In-depth manuscript review; recommends publication |

IMPLICATIONS

Ability to Utilize Simple Mechanical Energy to Initiate & Control Nuclear (Fusion) Forces

-Applications? -- ($\sim 10^3$ Mbar, 10^7 K)

--> Non-Power

- Pulsed neutron/gamma source (on/off)
- Radiography, therapy, irradiation
- Explosives detection; Spectroscopy
- Tritium (SNM) production
- Materials synthesis (C \rightarrow D)
- Chemical kinetics research at extreme conditions
 - (10^2 - 10^3 Mbar; 10^7 K)

--> Optimization/Scalability Potential Research (Phase 2 Focus)

ON-GOING INVESTIGATIONS

Assisting World-wide Groups - Set up independent capabilities

Assess Near-Term Applications Potential:

-Neutron-Gamma source, SNM production, Materials/Chemical Synthesis, etc.

System Optimization & Alternate Concepts:

- Nucleate without external neutron source (alphas, fps- in progress; lasers, lithotripters)
- Alternate liquids and combinations for enhanced implosion dynamics (in-progress)
- Increase driving head and improve reaction cells to enable continuous operations

Theoretical Modeling & Physics Understanding

-Nuclear-cum-Thermal-Hydraulics of Extremely Stressed States - System Interactions

Scalability potential - Variation of Nuclear Output with

- Drive amplitude, focusing and confinement time
- Liquid thermal-hydraulics
- Bubble cluster formation, quantity and duration
- Control dynamics (prevent runoff); Safety

** Need > 5+ orders of magnitude scaleup to attain break-even **

Rusi Taleyarkhan

CHALLENGES/OPPORTUNITIES

Thermal-Hydraulics

Nuclear Science/Engineering

Chemistry

Power Management / Control

Structural / Materials

Safety

Adaptability

Applications

-Hydrocode simulations / experimental data indicate

$\sim 10^3$ Mbar compressions, $\sim 10^7$ K temperatures

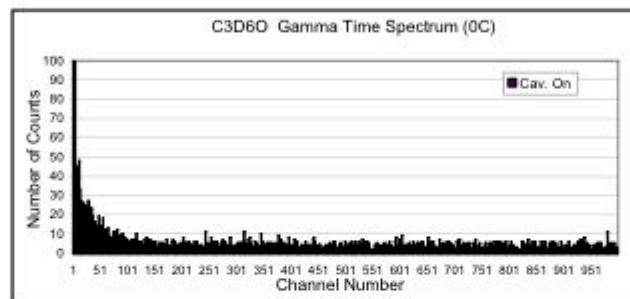
What could one do with such a system?????

Why are the new neutron-gamma data better (more compelling) than those reported earlier (Science, 2002) with a 15+y old Elscint (ET) detector ?

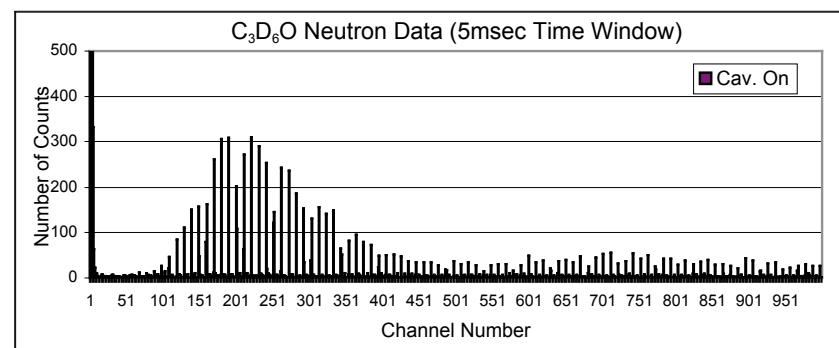
- Detection efficiency new LS detector > 10 x Efficiency of ET detector.
- We procured a new liquid scintillation (LS) detector system and electronic components
(Note: Aging w/o purging has a quenching effect on neutron counts, esp. low energy neutrons).
- More extensive calibration with Linac (TOF), PNG, Pu-Be, Co, and Cs.
- The neutron detection limit was lowered to ~0.7 MeV for the new LS vs ~2 MeV for ET detector.
Note: \square increases logarithmically with reduced bias (see \square vs light output curves).
- Using newly acquired multi-channel scaling boards, data were obtained over the entire 5,000 \square s between bubble bursts vs 0-100 \square s in earlier reported results.
- We also obtained spectra for gamma emissions this time (not done for the earlier reported work).
- Table 1 summarizes the differences between the system used earlier (with the ET detector) and the new (LS) detection system.

**Ensured SL time correlated signals are neutrons not gammas ?
YES! Gated on neutrons and separately on gammas.**

GATING ON GAMMAS

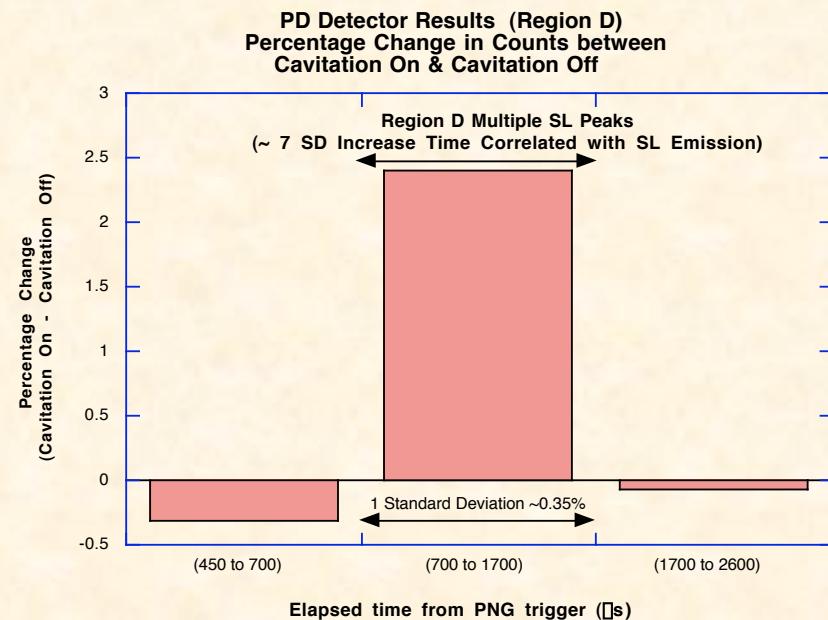
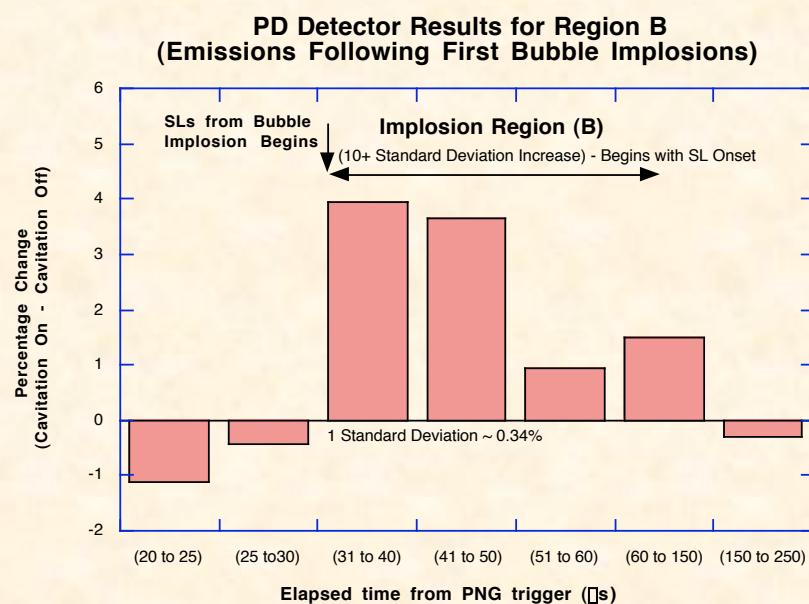


GATING ON NEUTRONS



Reconciling with measurements taken by Shapira (independent PD detection system)

- > PD system also measured statistically significant ($10+ SD$) $10^4 \sim 10^5 n-\mu\text{s}$ EXCESS NUCLEAR EMISSIONS in tests with $\text{C}_3\text{D}_6\text{O}$
 - > at and during SL emission
 - > Differences vs Tritium data reconciled (no T data obtained)



→INDEPENDENT CONFIRMATION OF A KEY FINDING:
→ $n-\mu$ s are emitted from neutron cavitated $\text{C}_3\text{D}_6\text{O}$